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Seismic response of liquid-containing tanks with emphasis on the hydrodynamic response and near-fault phenomena

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ABSTRACT

The present research studies the hydrodynamic response of cylindrical liquid-containing tanks with stiff walls under seismic excitations. Starting from standard hydrodynamic assumptions, the fluid oscillatory modes are separated to an impulsive mode and convective modes through the introduction of a reference frame co-moving with the base of the tank. The response of the fluid's normal modes to a lateral excitation and the role of Housner's oscillators is elucidated. Fast Fourier Transform techniques are applied to samples of earthquake records with near- and far-fault characteristics that have been appropriately scaled to match the Eurocode 8 design spectrum. Critical response quantities including the base shear and the height of the sloshing wave are computed analytically as functions of time and results are compared for near- and far-fault conditions. Particular emphasis is given on the contribution to the above quantities of the second convective mode which is systematically neglected according to current design practices for liquid-containing tanks. The results suggest that under near-fault conditions, when the directivity pulse has substantial content near the frequency of the second convective mode, current provisions may lead to a significant underestimation of the maximum height of the sloshing wave. This observation may provide an explanation of the extensive post-earthquake damage observed at many tank roofs located in the proximity of active faults. The results for near-fault records are compared with those obtained from a simplified representation of the velocity pulse proposed in the literature. The simplified wavelet leads to acceptable accuracy compared with a corresponding real record when the maximum height of the sloshing wave is examined; however, significant underestimation is detected for the calculation of the base shear.

1. Introduction

Storage tanks are widely used in many industrial facilities and especially in the oil and gas industry. The consequences in the case of serious damage suggest not only a significant loss of economic value but also possible environmental damage. The importance of these facilities for local economy necessitates their functionality after major earthquake events; thus, the seismic performance of liquid storage tanks is an issue of particular importance. Numerous damages have been reported in tanks after significant earthquakes, such as the 1979 Imperial Valley Earthquake in USA [1], the 1999 Kocaeli Earthquake in Turkey [2] and the 2011 Tohoku Earthquake and Tsunami in Japan [3]. Observations on damage after major earthquake events may provide insight in the various failure modes and the possible areas where the design process may need further elaboration.

According to the report of Zama et al. [3] damage to oil storage tanks is classified into three types: external forces as the case of tsunami waves, long-period ground motions, and short-period strong ground motions. Following Priestley et al. [4], Barros [5], and the 2011 guidelines of the Petrochemical Committee of the Energy Division of the American Society of Civil Engineers [6] some of the most observed types of failure include:

(a) Buckling of tank wall above base known as "elephant foot bulge", which typically occurs around the perimeter of unanchored tanks attributed to large compressive stress of the tank wall. Another less common and less damaging buckling mode of the tank shell is the "diamond shape" buckling, usually associated with taller tanks with very thin shells.

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(b) Damage of the upper shell of the tank wall and/or roof as well as failure of frangible joints between wall and roof due to long-period sloshing of fluid and hydrodynamic pressure.
(c) Weld failure between the bottom plate and the tank shell as a result of high-tension forces during uplift.

The behavior of a storage tank during an earthquake depends on several different factors including: (i) the structural details of the tank, such as type of tank, material and size, foundation and bearing structure; (ii) the characteristics of the seismic motion; (iii) any post-earthquake ground displacements that may take place, such as ground sliding and liquefaction; and (iv) the properties of the soil. The significance of fluid-structure interaction effects has been extensively addressed in the literature for several types of structures including locks and dams (see e.g. [7–10]). This paper focuses on the response of a rigid liquid-filled cylindrical tank that is rigidly fixed on the ground. The fundamental mathematical formulation and treatment of the problem has been initially given by Housner [11–13] who proposed the separation of the sloshing oscillations to one impulsive mode accounting for the part of the liquid that rigidly follows the tank walls and a series of convective modes referring to the part of the liquid that oscillates independently from the tank walls. The contribution of the impulsive mode was studied in depth by Jacobsen [14]. Interest in the problem was further incited following the 1964 Alaskan earthquake, that "caused the first large-scale damage to tanks of modern design and profoundly influenced the research into their vibrational characteristics" as pointed by Haroun [15]. In contrast to Housner, who worked with a simplified version of the underlying hydrodynamics, Veletsos [16,17] in his pioneering work elaborated on the fluid dynamics of an incompressible, inviscid liquid. This approach has been extended to the case of a flexible tank by Haroun [16]. Parallel to the concerns of seismologists, NASA engineers have worked in the 1950s and 1960s on the sloshing modes excited in rockets by high accelerations. Their approach and results can be found in [18].

Liquid storage tanks fall in the class of structures (together with, e.g., high-rise buildings and suspension bridges) with large fundamental period. Thus it is of interest to consider excitations with long-period components that may be generated by either far-source large crustal earthquakes through the help of path effects or by near-fault earthquakes through forward rupture directivity and fling-step effects [19–21]. In fact the results of long-period ground motions can be identified through the damage caused to tanks by liquid sloshing that has been identified repeatedly in the past after major earthquakes [19].

In this paper the hydrodynamic response of liquid-containing tanks with rigid walls is examined under seismic excitations. A concise theoretical background is provided and, contrary to current practice, the basic equations are developed with the aid of a reference frame co-moving with the tank base. Emphasis is placed on a velocity potential Φ that gives rise to the velocity of the fluid relative to the tank, the subsequent definition of the fluid's normal modes and the introduction of Housner's oscillators connected to the above modes. This approach leads to a clear identification of impulsive and convective modes through their contribution to the lateral force as is elaborated in the following.

Increased computational capacity of software programmes has spurred interest to simulate the hydrodynamic response of liquid storage tanks with the aid of finite element methods, e.g. [22–25]. These techniques allow a more thorough study of various phenomena such as fluid-structure interaction and non-linearity of sloshing amplitude.

Virella et al. [22] use a general-purpose FE software to address tank flexibility and study the impulsive modes of vibration of cylindrical rigid tank-liquid systems under horizontal motion for various H/R ratios. Results confirm that accurate predictions regarding the impulsive response of a liquid can be made by considering just the fundamental mode ($n = 1$), regardless of the height-to-tank diameter ratios, while differences between the impulsive pressure distributions calculated considering flexible and rigid tanks increase with the aspect ratio (H/R) of the tanks.

Moslemi et al. [23] and Yazici [24] compared results of FE techniques with the simplified spring mass analogue model. An overall good agreement was found for maximum wave height of a tall tank with an aspect ratio $H/R = 3.0$ leading to a 25% underestimation for near-fault records [24]. Also, a good agreement was observed regarding base shear and overturning moments of elevated tanks incorporating fluid structure interaction in FE [23].

Goudarzi and Sabbagh-Yazdi [25] used FEM to perform modal and nonlinear response-history analysis of three vertical cylindrical tanks in the three-dimensional space. Results confirm that the effect of higher sloshing modes should be taken into account when calculating the maximum sloshing wave height, as waves occurring in the middle of free surface may be computed 70% greater than those that occur at the side walls of the tank; however they highlight that the simplified Mass Spring Models (MSM) may not predict the maximum wave height with satisfactory accuracy in the case of broad tanks (with $H/R < 0.5$) because of the effect of non-linearity.

Many studies involving numerical simulations with FE confirm the applicability of the spring-mass analogue in practise, e.g. [22–24], while this approach is currently suggested by many design codes including Eurocode [26]. The present research serves as a basis to understand these more complex problems by providing a comprehensive and concise derivation of the fundamental equations that govern the tank liquid seismic motion; thus, allowing to focus on the effect of the frequency content of near-fault seismic motion.

The principal motivation of the research is to assess the accuracy of many current seismic design codes including Eurocode 8 [26] according to which the second convective mode may be neglected when calculating the response quantities of an accelerating tank. It is examined whether near-fault earthquake records with forward directivity characteristics may excite the second convective mode to such an extent that should not be neglected for design purposes. Also, the applicability of simple wavelets that model near-fault phenomena in the estimation of critical response quantities is examined. Simplified representation of actual pulse-like near-fault earthquake records with use of wavelets has gained the interest of researchers during the last years, e.g. [27–29]. These mathematical formulations involve parameters that represent specific seismological features, such as earthquake magnitude and distance. Furthermore, their mathematical simplicity, may allow the derivation of closed-form solutions facilitating parametric analyses, e.g. [30].

The results suggest that neglecting the significant second convective mode for near-fault conditions in the calculation of the maximum height of the sloshing wave leads to significant error. On the other hand, total base shear is accurately estimated considering only the first convective and impulsive modes for both near- and far-fault excitations. The simplified wavelets examined in this work provide acceptable accuracy regarding the height of the sloshing wave, while significant residuals are detected in the estimation of base shear.

2. Hydrodynamics of sloshing

The problem examined in the present work involves a rigid cylindrical tank rigidly fixed on the ground containing an incompressible, inviscid fluid with an irrotational flow field. Small deviations of the free liquid surface from equilibrium are assumed;